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P. Beiersdorfer, G. Brown, A. Laska

June 23, 2016

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Searching for Dielectronic Satellite Lines Associated with $3s \rightarrow 2p$ Transitions in Fe XVII

P. Beiersdorfer, G. V. Brown, and A. Laska

Physics Division, Lawrence Livermore National Laboratory, Livermore, CA 94550, USA

Abstract.
Using the electron beam ion trap facility at Livermore we have performed controlled laboratory measurements to search for dielectronic satellite transitions associated with the three strong $3s \rightarrow 2p$ transitions in the Fe XVII spectrum. These transitions fall into the 16.5 - 17.1 Å wavelength range. Surprisingly, we find that even the two strong, electric dipole allowed $3s \rightarrow 2p$ transitions are not associated with any substantial amount of dielectronic satellite lines. Dielectronic satellite lines are only associated with the two strongest $3d \rightarrow 2p$ transitions located near 15 Å.

1. INTRODUCTION

Dielectronic satellite emission has been shown to contribute to the L-shell x-ray spectra of highly charged iron. For example, essentially all $n = 3 \rightarrow n = 2$ transitions of carbonlike, boronlike, berylliumlike, and lithiumlike iron situated in the 10.5 to 15.5 Å region blend with unresolved dielectronic satellite lines that involve a so-called spectator electron with a high principal quantum number $n \geq 4$ [1]. L-shell dielectronic satellite lines also have been shown to play a role in the L-shell x-ray emission of Fe XVIII [2], where they have a potential use as temperature diagnostics.

Dielectronic satellite lines are produced by resonant electron capture and subsequent radiative decay [3]. For dielectronic satellite lines associated with the $3\ell' \rightarrow 2p$ L-shell lines of Fe XVII these processes can be described as:

$$1s^2 2s^2 2p^6 + e^- \rightarrow 1s^2 2s^2 2p^5 n\ell n'\ell' \rightarrow 1s^2 2s^2 2p^6 n'\ell' + h\nu \qquad (1)$$

The strongest such satellite lines $h\nu$ are those with $n = n' = 3$. However, even these lines are not easily detected in typical astrophysical or laboratory plasmas. Moreover, the upper levels produced by dielectronic recombination can also be produced by collisional excitation so that it is challenging to tease apart the line formation mechanisms. As a result, the $n = 3 \rightarrow n = 2$ Fe XVI x-ray lines detected so far in low-density coronal plasmas are lines that are excited mostly by electron impact excitation [4, 5, 6, 7, 8]. The only lines of Fe XVI produced purely by dielectronic recombination identified to date are those lines with an $n' = 4$ spectator electron. These were found in the spectrum of the corona of the star Capella observed with the Chandra X-ray Observatory [9]. However, the feature produced by these lines is very weak.

Using the Livermore electron beam ion trap facility we can select the line formation process and, thus, record lines that are specifically produced by dielectronic recombination. In fact, we have recently used this facility to identify the dielectronic satellite lines associated with one of the electric-dipole allowed $3d \rightarrow 2p$ transition in Fe XVII [10], which is labeled 3C in standard notation [11, 12].

We have now extended our laboratory measurements to search for dielectronic satellite transitions associated with the three $3s \rightarrow 2p$ transitions labeled 3F, 3G, and 3H, which are among the strongest lines in the Fe XVII spectrum. Surprisingly, we find that even the two strong electric dipole allowed $3s \rightarrow 2p$ transitions are not associated with any substantial amount of dielectronic satellite lines.

2. EXPERIMENTAL SETUP

The present measurements were carried out on the Livermore electron beam ion trap facility [13]. It uses a mono-energetic electron beam to produce, excite, and trap ions of the desired charge state. In order to measure the emission

from Fe XVII and its satellite lines, we employed a crystal spectrometer [14] that covered the iron L-shell emission between about 15.0 and 17.5 Å. The spectrometer was equipped with a thin-window proportional counter [15] that detected individual x rays diffracted by the crystals.

A window-less, cryogenically cooled Si(Li) solid-state detector was used to monitor the overall x-ray emission from the ion trap. The Si(Li) detector has a relatively poor energy resolution of about 150 eV, which is much worse than that of the EBIT x-ray calorimeter (ECS) we also use to monitor the machine's x-ray emission [16, 17]. However, it has a two order of magnitude higher count rate than the ECS so that we can monitor the trap's performance in real time.

Dielectronic recombination is a resonant process, i.e. the energy of the free electron e^- must be such that upon capture into a level $n'\ell'$ it gives off the correct energy to promote a bound electron from an $n = 2$ level to a level $n\ell$. Emission from dielectronic satellites is, therefore, produced when we set the beam energy to the resonance energy. Sitting on a given resonance, however, also depletes the available number of Fe^{16+} ions. As a result, we measure dielectronic resonance features by sweeping over the resonances in a sufficiently quick manner to avoid substantial depletion, as described in earlier experiments [18, 19, 20, 21].

In the present experiment we swept the electron beam energy from well below the resonance energy to excite the $1s^2 2s^2 2p^5 3\ell 3\ell'$ resonances, which are located at about 400 eV, to well above the threshold energy for exciting the Fe XVII lines. In fact, we have chosen the upper energy to be just below the ionization potential of Fe^{16+}. This choice maximizes the abundance of Fe^{16+} ions in the trap. The energy needed to excite the $3s \rightarrow 2p$ transition wtih the longest wavelength is about 700 eV. It is larger for the more energetic lines of Fe XVII; e.g., the threshold energy of line $3C$ is about 830 eV.

Data from the crystal spectrometer and the Si(Li) detector were acquired using an event-mode data acquistion system [22]. Each x-ray event is tagged with the energy of the electron beam as well as the time within the sweep cycle.

3. RESULTS AND DISCUSSION

The x-ray emission recorded with the Si(Li) detector as a function of beam energy is shown in Fig. 1. As Fig. 1 shows, our measurements resolve the resonances with spectator electrons $n' = 3$ and 4. The resonances with $n' \geq 5$ are closely spaced in energy and in part overlap with each other. Moreover, the electron beam energy has an energy spread of about 30 to 50 eV [23, 24], which makes it impossible to resolve resonances that are spaced closer than this spread.
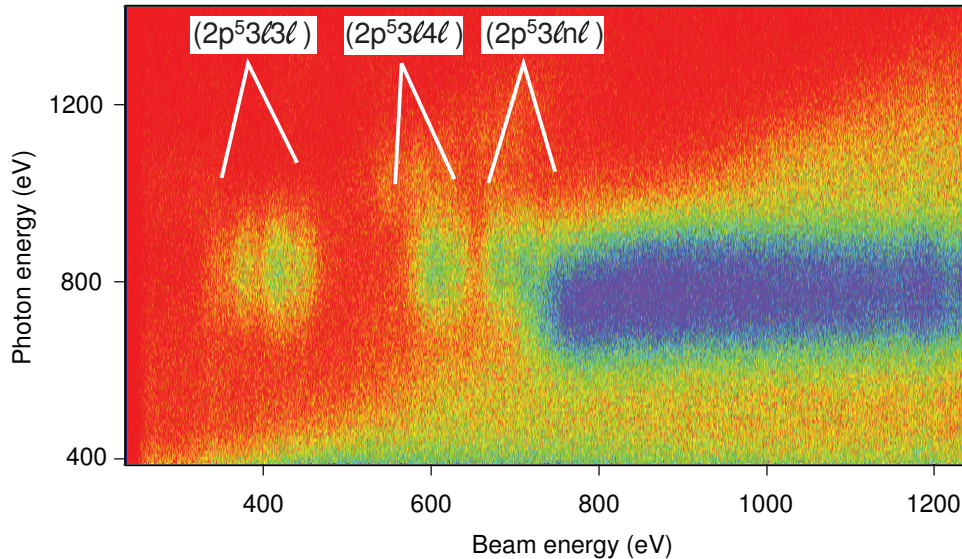

FIGURE 1. L-shell x-ray emission from iron ions recorded with a Si(Li) detector as a function of electron beam energy. The location of the resonances with spectator electrons $n' = 3$ and 4 and those with $n' \geq 5$ are marked.

The resolution of our crystal spectrometer (about 1.5 eV) greatly exceeds that of the Si(Li) detector. As a result, measurements with the crystal spectrometer clearly resolve individual x-ray lines. The x-ray emission observed with

our crystal spectrometer as a function of beam energy is shown in Fig. 2. The spectrometer covers the range of the $(1s^2 2s^2 2p^5_{3/2} 3s_{1/2})_{J=1,2} \rightarrow 1s^2 2s^2 2p^6_{J=0}$ lines labeled 3G and M2, the $(1s^2 2s^2 2p^5_{1/2} 3s_{1/2})_{J=1} \rightarrow 1s^2 2s^2 2p^6_{J=0}$ line labeled 3F and the $(1s^2 2s^2 2p^5_{1/2,3/2} 3d_{3/2,5/2})_{J=1} \rightarrow 1s^2 2s^2 2p^6_{J=0}$ lines labeled 3E, 3D, and 3C. Here we use standard notation introduced by Parkinson and others [11, 12, 25, 26]. All of these lines are electric dipole transitions, except line M2, which is a magnetic quadrupole transition.
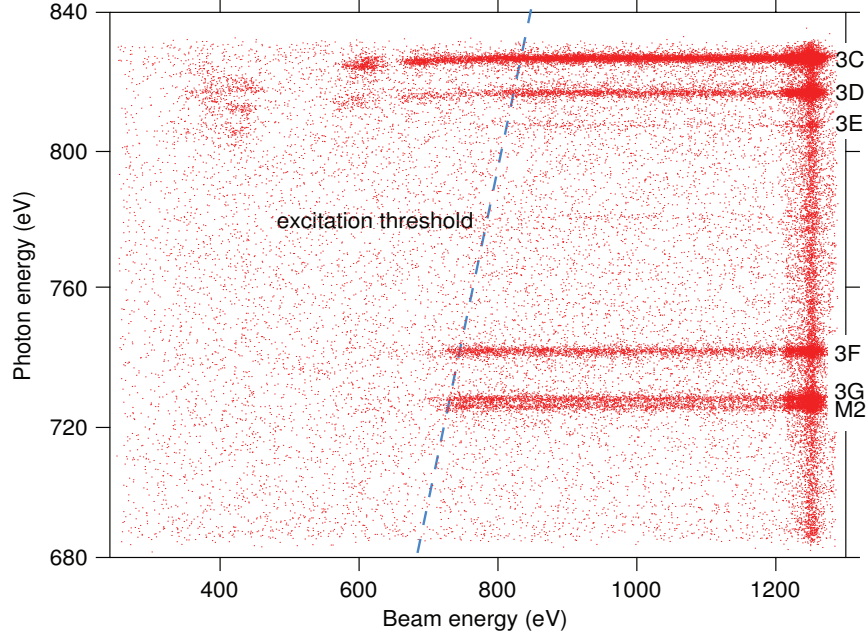

FIGURE 2. Crystal spectrometer measurement of the Fe XVII x-ray emission as a function of electron beam energy. The bright emission labeled 3C, 3D, 3F 3G, and M2 are Fe XVII transitions. The (blue) dashed line delineates the threshold for electron impact-excitation. X rays emitted at electron beam energies below this line are from dielectronic recombination.

As we have already mentioned in connection with Fig. 1, x-ray emission produced at beam energies below the threshold energy for exciting a given line is the result of dielectronic recombination. As seen from Fig. 2, only lines 3C and 3D are associated with x-ray emission excited at beam energies below their threshold energies. We detect no such below-threshold emission associated with lines 3F, 3G, and M2. Our measurement, thus, demonstrates that the $3s \rightarrow 2p$ transitions are not associated with dielectronic satellite lines. This is surprising, given that two of the three $3s \rightarrow 2p$ transitions are electric dipole allowed transitions with a large radiative decay rate that should favor radiative stabilization of doubly excited states produced by dielectronic capture.

An analysis of the dielectronic satellite features associated with the two strongest $3d \rightarrow 2p$ transitions is in progress. The $n' = 3$ features have a lot of spectral structure. In addition, both $3d \rightarrow 2p$ lines are associated with a continuous set of high-n dielectronic satellites. The intensity of these satellites smoothly maps onto the intensity of the $3d \rightarrow 2p$ lines as the electron energy crosses the excitation threshold. A similar behavior of the x-ray excitation function has been observed for the K-shell x-ray lines of heliumlike ions [27, 28, 29].

ACKNOWLEDGMENT

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